Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds

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LONG-TERM GOALS

The goal is to investigate, through theory and by analyzing existing data, sea surface physics and air-sea exchange in winds that range from weak to hurricane-strength. Ultimately, we want to develop unified parameterizations for the fluxes of momentum, sensible and latent heat, and enthalpy across the air-sea interface. These flux parameterizations will provide improved model coupling between the ocean and the atmosphere and, in essence, set the lower flux boundary conditions on atmospheric models and the upper flux boundary conditions on ocean models.

OBJECTIVES

1. Develop a theoretical framework for predicting air-sea fluxes from mean meteorological conditions and apply uniform analyses, based on this framework, to datasets that we will assemble.
2. Assemble a large collection of quality air-sea flux data that represents a wide variety of conditions.
3. Compute fluxes from these datasets using an improved analysis that better accommodates measurements made over heterogeneous surfaces, such as coastal zones. Focus the analyses on common problems where existing bulk formulations perform poorly—such as over surface heterogeneity, in weak winds, and in very strong winds.
4. Develop a unified algorithm for predicting the turbulent air-sea surface fluxes that spans the environmental range in our datasets, obeys theoretical principles and constraints, and substantially exceeds the correlation due to fictitious correlation.

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APPROACH

Andreas and Mahrt bring diverse expertise to this project. Mahrt has recently been focusing on boundary-layer processes in weak winds, when stratification and surface heterogeneity are important issues and when Monin-Obukhov similarity theory breaks down. Andreas, in contrast, has been concentrating on high winds, when sea spray becomes an important agent for modifying the usual interfacial fluxes of momentum, heat, and moisture. In additions, Dean Vickers of Oregon State University is a contractor on this project. Vickers brings expertise in processing large datasets—especially, aircraft data—and in parameterizing air-sea exchange. Together, we will develop flux parameterizations that span wind speeds from near zero to hurricane-strength.

Traditionally, the air-sea fluxes of momentum (τ, also called the surface stress), sensible heat (H_s), latent heat (H_L), and enthalpy (Q_{en}) are formulated as down-gradient fluxes that are compatible with Monin-Obukhov similarity theory:

$$\tau \equiv \rho u_*^2 = \rho C_{Dr} U_r^2 , \tag{1a}$$

$$H_s = \rho c_p C_{Hr} U_r \left(\Theta_{sfc} - \Theta_r\right) , \tag{1b}$$

$$H_L = \rho L_v C_{Er} U_r \left(Q_{sfc} - Q_r\right) , \tag{1c}$$

$$Q_{en} = \rho C_{Kr} U_r \left[c_p \left(\Theta_{sfc} - \Theta_r\right) + L_v \left(Q_{sfc} - Q_r\right)\right] . \tag{1d}$$

Here, ρ is the air density; c_p, the specific heat of air at constant pressure; L_v, the latent heat of vaporization; U_r, the wind speed at reference height r; Θ_r and Q_r, the potential temperature and specific humidity at r; and Θ_{sfc} and Q_{sfc}, the surface temperature and specific humidity. Equation (1a) also defines the friction velocity u_*.

The crux of most flux algorithms is in how they parameterize the transfer coefficients appropriate at reference height r: C_{Dr}, C_{Hr}, C_{Er}, and C_{Kr} in (1). A vast amount of air-sea interaction literature describes parameterizations for these quantities. In this project, however, we take a different approach. Andreas (1992, 2010, 2011; Andreas and Emanuel 2001; Andreas and DeCosmo 2002; Andreas et al. 2008) has suggested repeatedly that, when sea spray becomes a significant agent in air-sea exchange, (1b)–(1d), in particular, are not accurate. Moreover, spray-mediated exchange becomes “significant” (at least a 10% effect) at modest winds speeds, 12–15 m/s.

To account for spray effects, we formulate the total scalar fluxes as

$$H_{s,T} = H_s + Q_{s,sp} , \tag{2a}$$

$$H_{L,T} = H_L + Q_{L,sp} , \tag{2b}$$

$$Q_{en,T} = H_s + H_L + Q_{en,sp} . \tag{2c}$$

In these, subscript T denotes the total flux across the air-sea interface. The first term on the right [first two terms in (2c)] is the *interfacial* flux, parameterized as in (1); and the right-most term is the *spray-*

mediated flux. Because the spray-mediated fluxes do not scale the same way that the interfacial fluxes do [i.e., according to (1)], the traditional transfer coefficients C_{Hr}, C_{Er}, and C_{Kr} are inaccurate for parameterizing the total fluxes $H_{s,T}$, $H_{L,T}$, and $Q_{en,T}$ in high winds (Andreas 2011). In fact, Andreas (2011) recently demonstrated that, when spray-mediated transfer is in play, sensible heat fluxes can at times be countergradient, contrary to the assumption on which (1b) is based.

To address these various ideas, we have assembled—and are still assembling—a large set of air-sea flux measurements. We currently have in hand 20 datasets comprising about 7000 air-sea flux measurements. In this set, surface-level wind speeds range from near zero to 72 m/s; and sea surface temperatures range from –1° to 30°C. This dataset thus covers almost all oceanic conditions. Flux parameterizations developed from these data should, indeed, be "unified."

WORK COMPLETED

We investigated the variation of the sea-surface sensible heat flux on multiple scales using data from the Gulf of Tehuantepec Experiment (GOTEX; e.g., Romero and Melville 2010) and from eight additional aircraft datasets. We applied preliminary quality control to the nine datasets and discovered an artificial dependence of measured wind speed on aircraft heading in several of the datasets. As a result, NCAR has reprocessed the GOTEX data. Using these aircraft datasets, we have also carried out a study of the variation of the surface heat flux and drag coefficient.

Recently, Foreman and Emeis (2010) suggested that the drag coefficient formulated as (1a) is ill-posed and, instead, tried the drag relation

$$u_* = a\,U_{N10} + b \tag{3}$$

for aerodynamically rough flow. In (3), U_{N10} is the neutral-stability wind speed at a height of 10 m. On the basis of, perhaps, a thousand data points from the literature, Foreman and Emeis confirmed (3) and found $a = 0.051$ and $b = –0.14$ when both u_* and U_{N10} are in m/s.

The interesting feature of (3) is that, because b is negative, it naturally predicts a maximum value for the neutral-stability, 10-m drag coefficient (C_{DN10}):

$$C_{DN10} \equiv \left(\frac{u_*}{U_{N10}}\right)^2 = \left(\frac{a\,U_{N10} + b}{U_{N10}}\right)^2 = a^2\left(1 + \frac{b}{a\,U_{N10}}\right)^2 . \tag{4}$$

Such a limited drag coefficient in high winds is compatible with modern hurricane models (Jarosz et al. 2007; Moon et al. 2007; Sanford et al. 2007; Chiang et al. 2011).

Because (3) is in line with our goal of developing a new framework for parameterizing air-sea interaction that relies less on Monin-Obukhov similarity theory, we investigated it ourselves with much more data than Foreman and Emeis (2010) had. Figures 1 and 2 show our results.

A critical part of developing parameterizations is validating them. We therefore divided our datasets into two parts—primarily chronologically according to when we obtained the data. Figure 1 shows our "original" data, which come from ships, towers, and aircraft; Figure 2 shows our later data, which are all aircraft data obtained generally at altitudes less than 40 m.

In both Figures 1 and 2, the data clouds change character in the U_{N10} range 8–10 m/s. For wind speeds below this range, the points tend to turn toward the aerodynamically smooth limit, where the roughness length is given as

$$z_{0s} = 0.135 \frac{\nu}{u_*} . \tag{5}$$

Here, ν is the kinematic viscosity of air. Hence, in both Figures 1 and 2, we fitted only the data for which $U_{N10} \geq 9\,\mathrm{m/s}$ with (3).

In Figures 1 and 2, the results are, respectively,

$$u_* = 0.0581 U_{N10} - 0.214 , \tag{6}$$

$$u_* = 0.0584 U_{N10} - 0.245 . \tag{7}$$

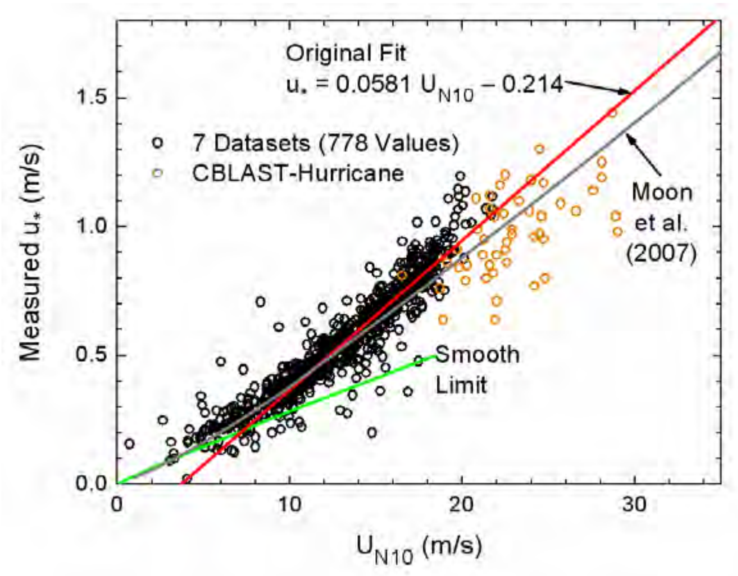

Figure 1. Eddy-covariance measurements of the friction velocity u_* from our "original" dataset of ship-board, tower-based, and aircraft data are plotted against the neutral-stability, 10-m wind speed U_{N10}. The red line, Eq. (6), is the best fit through data in the aerodynamically rough regime, $U_{N10} \geq 9\,\mathrm{m/s}$. ***The green line shows the aerodynamically smooth limit. The gray line is the drag relation that Moon et al. (2007) inferred from their hurricane simulations. The orange points are the aircraft data from the CBLAST hurricane flights (French et al. 2007) and are ignored in our fitting of the red line.***

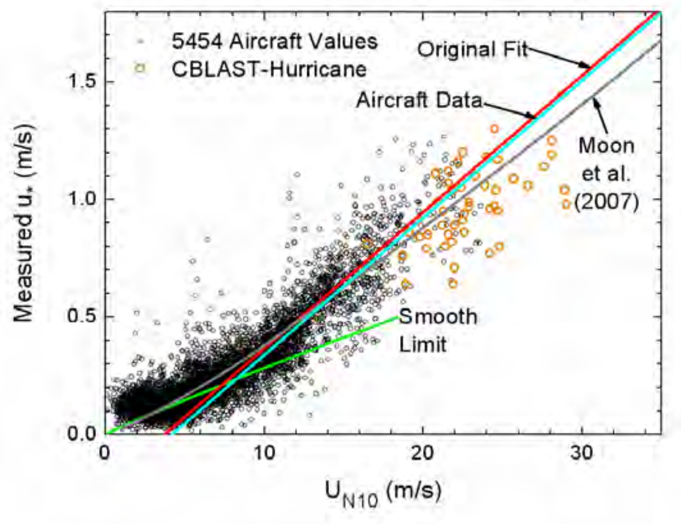

Figure 2. As in Figure 1, except these data are from our more recent set and were all collected by low-flying aircraft. The blue line, Eq. (7), is the fit to the data here in the aerodynamically rough regime, $U_{N10} \geq 9\,\mathrm{m/s}$***, and is almost indistinguishable from the red line, the fit to the data in Figure 1***

In both of these, u_* and U_{N10} are in m/s. The two lines are almost indistinguishable, as Figure 2 shows. In other words, we validate (6) with (7), or vice versa.

RESULTS

For all of the nine "later" aircraft datasets, upward heat flux is observed for slightly stable conditions (Figure 3). The magnitude of this "countergradient'" heat flux increases with wind speed and is possibly related to sea spray or microscale variations of surface temperature on the wave scale. Mesoscale heterogeneity of the sea surface temperature (SST) can also produce an upward area-averaged sensible heat flux for slightly stable conditions (Mahrt and Khelif 2010), but such mesoscale variability cannot explain the general increase of the countergradient heat flux with increasing wind speed.

In an effort to reduce offset errors and different SST processing and calibration procedures among field programs, we adjusted the SST in each field program to minimize the countergradient flux for weak winds. With or without this adjustment, for the combined dataset in Figure 3 (lower panel), the extent of the upward heat flux for weakly stable conditions increases systematically with wind speed.

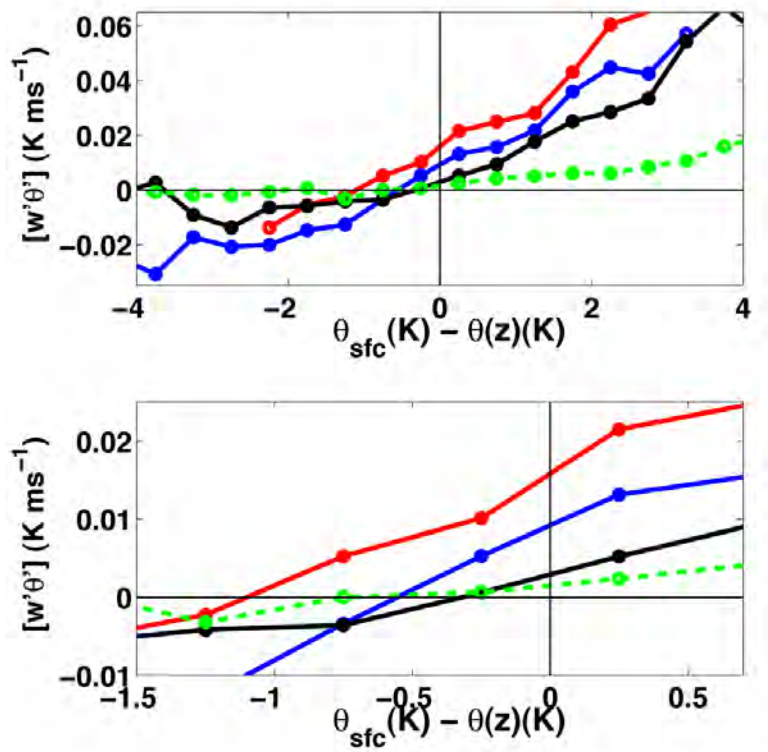

***Figure 3.** The kinematic surface sensible heat flux, w'θ', from 4-km flight segments for all nine aircraft field programs in our "later" dataset is composited over intervals of $\Theta_{sfc} - \Theta(z)$, where Θ_{sfc} is the surface temperature and Θ(z) is the potential temperature at flight level. Upper panel: the basic compositing, where the 10-m wind speeds are < 7 m/s (green), 7–14 m/s (black), 14–21 m/s (blue), and > 21 m/s (red). Lower panel: same as above but focusing on near-neutral conditions. In weakly stable conditions, $\Theta_{sfc} - \Theta(z) \lesssim 0°C$, the sensible heat flux is countergradient and increases with increasing wind speed.*

In neutral stratification, the logarithmic profile gives the following relationship among u_*, U_{N10}, and z_0:

$$U_{N10} = \frac{u_*}{k} \ln(10/z_0) \ . \tag{8}$$

Here, k (= 0.40) is the von Kármán constant. As a result, we can estimate the roughness length (in meters) in aerodynamically rough flow from (3) as

$$z_{0r} = 10 \exp\left[\frac{-k(u_* - b)}{a\, u_*}\right] \ . \tag{9}$$

In turn, we can predict the roughness length as a function of u_* for any aerodynamic regime by adding (5) and (9):

$$z_0 = 0.135 \frac{\nu}{u_*} + 10 \exp\left[\frac{-k(u_* - b)}{a\, u_*}\right] \ . \tag{10}$$

This result also yields the 10-m, neutral-stability drag coefficient from (8) and the definition in (4):

$$C_{DN10} = \left[\frac{k}{\ln(10/z_0)}\right]^2 \ . \tag{11}$$

Figure 4 shows (11), where we have used the coefficients in (7) for a and b.

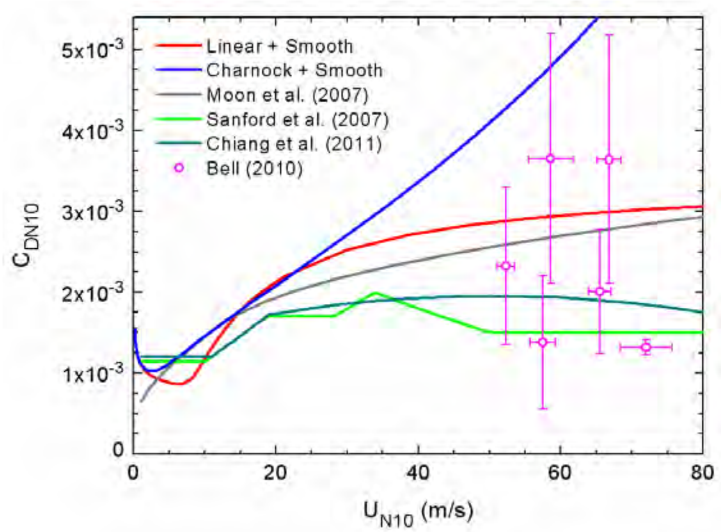

Figure 4. Various expressions for the neutral-stability, 10-m drag coefficient, C_{DN10}, as a function of U_{N10}. The red line is our result, (10). The blue line is a typical Charnock formulation. The gray line is the Moon et al. (2007) result, as in Figures 1 and 2. Sanford et al. (2007) and Chiang et al. (2011) attempted to fit the results that Powell et al. (2003) deduced from dropsonde profiles in tropical cyclones. The pink symbols are from Bell's (2010) angular momentum budgets for hurricanes Fabian and Isabel. His results are so scattered that they do not help us choose among the various models.

Figure 4 also shows other opinions as to the behavior of C_{DN10}. The "Charnock + Smooth" line combines the Charnock relation for z_{0r} with the aerodynamically smooth limit, (5), and is common in bulk flux algorithms (e.g., Fairall et al. 1996). Sanford et al. (2007) and Chiang et al. (2011) attempted to represent the C_{DN10} values from Powell et al. (2003) in their hurricane models. Sanford et al. used a piecewise-continuous fit to the Powell et al. data; Chiang et al. fitted them with an analytic function.

Moon et al. (2007) used a theoretical model for wind-wave coupling and flow separation in their hurricane simulations and inferred the roughness length from their modeled surface stress. The gray lines in Figures 1, 2, and 4 represent their analysis. They never presented their results as u_* versus U_{N10}, however, and therefore probably did not realize that their theory predicts, essentially, a straight-line relation between u_* and U_{N10} for U_{N10} above about 20 m/s. Mueller and Veron (2009) likewise produced the roll off in C_{DN10} by modeling just wind-wave coupling and flow separation.

Hence, we can tentatively conclude that wind-wave coupling and increasing wave sheltering is sufficient to explain the behavior of the drag coefficient in high winds. There is probably no need to postulate exotic mechanisms (mostly involving sea spray) to explain the roll off in C_{DN10} with increasing wind speed as Barenblatt et al. (2005), Makin (2005), and Soloviev and Lukas (2010), for example, have. Furthermore, because u_* seems to be linearly related to U_{N10} for all wind speeds in the aerodynamically rough regime, we see no obvious "drag crisis" (cf. Ingel 2011).

For comparison, Figures 1 and 2 show the CBLAST aircraft data that French et al. (2007) obtained in hurricanes Fabian and Isabel in 2003. In all cases, the aircraft never made flux measurements lower than 70 m, and half the runs were at 190 m and higher. French et al. tried to correct the flight-level momentum fluxes for the probable flux divergence associated with measurements this high but seem to have been not entirely successful: In Figures 1 and 2, these CBLAST data are biased low compared to the measurements nearer the surface. We have therefore not included these data in fitting (6) and (7). Bell (2010) estimated C_{DN10} from the angular momentum budget of an axisymmetric hurricane; his data came from dropsondes released in hurricanes Fabian and Isabel. Clearly, his C_{DN10} values are no use in evaluating which of the drag parameterizations depicted in Figure 4 is most realistic.

IMPACT/APPLICATIONS

Our inspection of the aircraft datasets has shown widespread problems: The measurements depend on aircraft heading with respect to the wind vector. We are continuing to work on this problem. Our analysis also indicates that current formulations of air-sea fluxes based on Monin-Obukhov similarity are not always well posed for data analysis, an effect that can mask important wave effects.

The behavior of the drag coefficient in tropical cyclones has been a crucial knowledge gap at least since Emanuel (1995) reported that hurricane models could not produce realistic storms if their drag parameterization was simply an extrapolation of drag relations obtained at lower wind speeds—like the "Charnock" relation in Figure 4. Equations (6) and (7) now provide a rational, data-based upper limit for C_{DN10} in hurricane-strength winds. Moreover, our analysis explains why C_{DN10} must roll off with increasing wind speed: There is no "drag crisis"; rather, there was a crisis in understanding how to formulate a drag law in high winds. Equation (3) seems to be an improved approach.

TRANSITIONS

Journal articles and conference presentations describe our work on air-sea exchange. Andreas has also developed a software "kit" that contains instructions and the Fortran programs necessary to implement a bulk air-sea flux algorithm that includes the spray effects we have described (see Andreas et al. 2008; Andreas 2010). The current version of that code is 3.4, and the kit is posted at http://www.nwra.com/resumes/andreas/software.php, where it can be freely downloaded.

Andreas is currently collaborating with hurricane modelers Isaac Ginis and Tetsu Hara of the University of Rhode Island to get these new parameterizations for the air-sea fluxes into their hurricane model.

RELATED PROJECTS

Andreas is in the second year of a three-year project funded under the National Ocean Partnership Program. This project is on "Advanced Coupled Atmosphere-Wave-Ocean Modeling for Improving Tropical Cyclone Prediction Models," with Isaac Ginis at the University of Rhode Island and Shuyi Chen at the University of Miami as lead PIs. Andreas is a subcontractor to the University of Rhode Island and will supply expertise, code, and analyses to help the project understand how sea spray affects hurricane intensity.

REFERENCES

Andreas, E. L, 1992: Sea spray and the turbulent air-sea heat fluxes. *J. Geophys. Res.*, **97**, 11,429–11,441.

Andreas, E. L, 2010: Spray-mediated enthalpy flux to the atmosphere and salt flux to the ocean in high winds. *J. Phys. Oceanogr.*, **40**, 608–619.

Andreas, E. L, 2011: Fallacies of the enthalpy transfer coefficient over the ocean in high winds. *J. Atmos. Sci.*, **68**, 1435–1445.

Andreas, E. L, and J. DeCosmo, 2002: The signature of sea spray in the HEXOS turbulent heat flux data. *Bound.-Layer Meteor.*, **103**, 303–333.

Andreas, E. L, and K. A. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity. *J. Atmos. Sci.*, **58**, 3741–3751.

Andreas, E. L, P. O. G. Persson, and J. E. Hare, 2008: A bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *J. Phys. Oceanogr.*, **38**, 1581–1596.

Barenblatt, G. I., A. J. Chorin, and V. M. Prostokishin, 2005: A note concerning the Lighthill "sandwich model" of tropical cyclones. *Proc. Nat. Acad. Sci.*, **102**, 11,148–11,150.

Bell, M. M., 2010: Air-sea enthalpy and momentum exchange at major hurricane wind speeds. Ph.D. dissertation, Naval Postgraduate School, Monterey, CA, 133 pp.

Chiang, T.-L., C.-R. Wu, and L.-Y. Oey, 2011: Typhoon Kai-Tak: An ocean's perfect storm. *J. Phys. Oceanogr.*, **41**, 221–233.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52**, 3969–3976.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young, 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment. *J. Geophys. Res.*, **101**, 3747–3764.

Foreman, R. J., and S. Emeis, 2010: Revisiting the definition of the drag coefficient in the marine atmospheric boundary layer. *J. Phys. Oceanogr.*, **40**, 2325–2332.

French, J. R., W. M. Drennan, J. A. Zhang, and P. G. Black, 2007: Turbulent fluxes in the hurricane boundary layer. Part I: Momentum flux. *J. Atmos. Sci.*, **64**, 1089–1102.

Ingel, L. Kh., 2011: On the effect of spray on the dynamics of the marine atmospheric surface layer in strong winds. *Izv., Atmos. Oceanic Phys.*, **47**, 119–127.

Jarosz, E., D. A. Mitchell, D. W. Wang, and W. J. Teague, 2007: Bottom-up determination of air-sea momentum exchange under a major tropical cyclone. *Science*, **315** (5819), 1707–1709.

Mahrt, L., and D. Khelif, 2010: Heat fluxes over weak SST heterogeneity. *J. Geophys. Res.*, **115**, D11103, 11 pp., doi: 10.1029/2009JD013161.

Makin, V. K., 2005: A note on the drag of the sea surface at hurricane winds. *Bound.-Layer Meteor.*, **115**, 169–176.

Moon, I.-J., I. Ginis, T. Hara, and B. Thomas, 2007: A physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane intensity predictions. *Mon. Wea. Rev.*, **135**, 2869–2878.

Mueller, J. A., and F. Veron, 2009: Nonlinear formulation of the bulk surface stress over breaking waves: Feedback mechanisms from air-flow separation. *Bound.-Layer Meteor.*, **130**, 117–134.

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag coefficient for high winds in tropical cyclones. *Nature*, **422** (6929), 279–283.

Romero, L., and W. K. Melville, 2010: Airborne observations of fetch-limited waves in the Gulf of Tehuantepec. *J. Phys. Oceanogr.*, **40**, 441–465.

Sanford, T. B., J. F. Price, J. B. Girton, and D. C. Webb, 2007: Highly resolved observations and simulations of the ocean response to a hurricane. *Geophys. Res. Lett.*, **34**, L13604, 5 pp., doi: 10.1029/2007GL029679.

Soloviev, A., and R. Lukas, 2010: Effects of bubbles and sea spray on air-sea exchange in hurricane conditions. *Bound.-Layer Meteor.*, **136**, 365–376.

PUBLICATIONS

Andreas, E. L, 2011: Fallacies of the enthalpy transfer coefficient over the ocean in high winds. *Journal of the Atmospheric Sciences*, **68**, 1435–1445.

Brooks, I. M., E. L Andreas, G. McFiggans, M. D. Anguelova, and C. O'Dowd, 2011: Primary marine aerosol fluxes: Progress and priorities (Meeting Summary). *Bulletin of the American Meteorological Society*, **92**, 489–491.

de Leeuw, G., E. L Andreas, M. D. Anguelova, C. W. Fairall, E. R. Lewis, C. O'Dowd, M. Schulz, and S. E. Schwartz, 2011: Production flux of sea-spray aerosol. *Reviews of Geophysics*, **49**, RG2001, 39 pp., doi: 10.1029/2010RG000349.

Jones, K. F., and E. L Andreas, 2011: Sea spray icing of fixed offshore structures. *Quarterly Journal of the Royal Meteorological Society*, in press.